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Initial efforts during the 4-year period of this grant involved investigations of the seasonal-latitudinal structure of the diurnal thermospheric tide and the thermospheric extensions of semidiurnal tides excited below 100 Km using a numerical model which realistically simulates dissipative processes. This work, combined with a calculation of the in-situ semidiurnal thermospheric tide, led to construction of a synthesized model of diurnal and semidiurnal temperatures and winds calibrated with incoherent scatter radar observations. (Cont.)

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This model was subsequently utilized to investigate tidal variations in thermospheric composition and the generation of electric fields and currents due to dynamo action in the E region. A rotating plane equivalent gravity wave formalism was also developed to more efficiently compute thermospheric tidal structures, and utilized to investigate the damping effect of O-N_2 mutual diffusion on thermospheric tides, and the mutual coupling between tides and turbulence in the mesosphere. Work under this grant formed an important contribution to a comprehensive review of theoretical studies of atmospheric tides written for Review of Geophysics and Space Physics in 1979. Finally, significant effects of tidal variations in temperature and density on the hydrated positive ion chemistry of the D region have been discovered, thus explaining some important aspects of the asymmetric and seasonal-latitudinal behavior of the D region.

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AFOSR-TR- 81-0349

BOSTON COLLEGE

SPACE DATA ANALYSIS LABORATORY

Final Scientific Report

for the research period

1 January 1977 through 31 December 1980

entitled

STRUCTURE OF THE UPPER ATMOSPHERE

Grant AFOSR-77-3223

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AFOSR/NC
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1 March, 1981

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OBJECTIVES

The primary objective of this research has been to improve our knowledge of the structure of the upper atmosphere, in particular concentrating on the phenomena of atmospheric tides which represent a major contribution to the dynamics of the atmosphere above 80 Km. This objective has been accomplished through numerical simulation of the upper atmosphere responses in temperature, winds, and composition to periodic thermal excitations in the troposphere, stratosphere, mesosphere, and thermosphere. The approach of calibrating the theoretical model with observed data has played an essential role in improving the accuracy of the model simulations for making predictions with regard to seasonal, latitudinal, and solar cycle variations of upper atmosphere structure, interpreting incoherent scatter radar and satellite accelerometer and mass spectrometer data, and for making recommendations for future observational programs.

PERSONNEL

Professional personnel partially supported under Grant AFOSR 77-3223 have included:

Dr. Jeffrey M. Forbes (principal investigator)

Ms. Maura Hagan (research analyst)

Ms. Carol Foley (research analyst/programmer)

In addition, at least one undergraduate student per year was supported part-time during the academic year and full-time in the summer.

DEGREES

"Thermospheric Tides: An f-Plane Approximation", M. E. Hagan, Master's Thesis, June, 1979.

ACCOMPLISHMENTS

The first effort completed under AFOSR Grant 77-3223 involved investigating the seasonal-latitudinal structure of the diurnal thermospheric tide for minimum and maximum levels of solar activity by numerically solving the linearized inseparable tidal equations for a spherical, rotating, viscous atmosphere with anisotropic ion drag. It was found that variations in F-region ionospheric structure and the solar zenith angle dependence of the EUV heat source are major factors controlling the seasonal-latitudinal structure of the diurnal thermospheric tide. The combined interaction of the solar-cycle dependent background temperature profile (which controls the altitude of diffusion dominance) and variations in the seasonal structure of the ionospheric plasma with sunspot activity leads to a solar-cycle variation of the seasonal-latitudinal morphology of the diurnal tide. For instance, summer-winter differences in tidal winds at a given height are more pronounced during SSMAX as opposed to SSMIN. At a given level of solar activity, westerly winds, vertical winds and temperatures are generally larger in the summer hemisphere, whereas the amplitude of the northerly wind is greatest during winter. There also exist summer-winter phase differences in the tidal fields ranging from 1 to 6 h, depending upon height, latitude and sunspot activity. Computations of diurnal oscillations in O and N_2 were performed which similarly demonstrate a complex dependence of tidal effects on height, latitude, season and solar activity. In particular, the temperature-atomic oxygen phase difference (the so-called "phase anomaly") at 3-0 km varies from about 7 to -2 h at SSMAX and 2 to -2 h at SSMIN, between 80°S and 80°N, respectively, at December solstice. The above results suggest that related seasonal-latitudinal and solar-cycle variations exist in midlatitude ionospheric structure, the F-region equatorial anomaly, the tidal distributions of O_2, Ar, He and H, and magnetic and electric fields generated by the E-region dynamo mechanism. Finally, it was concluded that static diffusion models based on families of empirical temperature profiles cannot simultaneously yield realistic diurnal variations in O, N_2 and temperature below 200 km for SSMIN and 300 km for SSMAX. This work was reported in Seasonal-Latitudinal Structure of the Diurnal Thermospheric Tide[1] by J. M. Forbes and H. B. Garrett.

The thermospheric propagation characteristics of upward-propagating semidiurnal tides excited below 100 km were then investigated using a modified version of the above numerical model. Although not published in the open literature, these results did appear in NRL memorandum report 3442 entitled Semidiurnal Hough Mode Extensions in the Thermosphere and Their Application by R. S. Lindzen, S. S. Hong, and J. M. Forbes, in 1977.

The above work led to the construction of a three-dimensional model of the thermospheric tidal structure for equinox conditions by synthesizing diurnal and semidiurnal components excited in situ and propagating upwards from the mesosphere and below. The individual tidal structures, which are inseparable in their latitude and height dependence, were each determined by solving the linearized tidal equations for a spherical, rotating, viscous atmosphere with anisotropic ion drag. The amplitudes and phases of the individual tidal components were calibrated in least-squares sense with incoherent scatter and satellite measurements of winds and temperature. The model was then used to make predictions regarding the variation of the thermospheric tidal structures with height, latitude, local time, and solar cycle, revealing many features of thermospheric structure which could not be recovered from any available combination of incoherent scatter and/or satellite measurements. The temperature and velocity fields are highly structured below 200 km, and contain a large semidiurnal component below 150 km at low- to mid-latitudes. The presence of a strong semidiurnal contribution at all heights is evident at latitudes less than 30° during all levels of solar activity for the velocity field. This is consistent with the relatively large semidiurnal (and possibly terdiurnal) component in the Arecibo meridional wind measurements, as opposed to the predominance of the diurnal component at Millstone Hill and St. Santin. This work is reported in Tidal Structure of the Thermosphere at Equinox[3], by H. B. Garrett and J. M. Forbes. The primary virtue of this composite model is that by calibration with data with limited spatial and temporal coverage it is possible to predict latitude, height, and solar cycle variations in tidal structure which cannot realistically be measured. It is useful in a variety of geophysical applications, particularly when a model of the thermospheric dynamics is needed and the only available observational data are under a different set of geophysical or geographical conditions. The model should greatly aid in interpretive analyses of the many segments of incoherent scatter data that are available with incomplete local time coverage, since in these cases it is impossible to separate the mean, diurnal and semidiurnal components. It can also provide an alternative theoretical constraint to separate the zonal and meridional wind components at an incoherent scatter facility such as Millstone Hill where the magnetic declination angle is not negligibly small. (Currently, such a theoretical constraint is provided from estimates of the thermospheric dynamics obtained by using pressure gradients from static diffusion models as forcing terms in the horizontal equations of the neutral gas).

In Tidal Variations in Thermospheric O, O_2, N_2, Ar, He, and H,[3] by J. M. Forbes, a formalism is developed for computing tidal variations in thermospheric composition and is used to investigate diurnal and semidiurnal variations in O, O_2, N_2, Ar, He and H at minimum and maximum levels of sunspot activity, given as input the temperatures and winds from the composite model described above. The model formally accounts for tidal temperatures, horizontal and vertical tidal winds, photochemistry and ion chemistry, thermal diffusion, and exospheric transport in determining the tidal variations of these constituents, as well as deviations from diffusive equilibrium in the time average component due to photochemistry, Jeans escape, or background vertical winds. Sunspot minimum calculations show excellent agreement with equatorial San Marco 3 Nace measurements in both amplitude and phase for diurnal and semidiurnal variations between 220 and 280 km. Major exceptions are the equatorial diurnal amplitude of Ar, which the model overestimates by 35%, and the equatorial diurnal amplitude of He, which the model underestimates by about 25%. Simulations for sunspot maximum conditions demonstrate substantial solar cycle differences in the vertical structures of amplitude and phase for each constituent and in the relative contribution of semidiurnal and diurnal components at different latitudes and heights. This study indicates a clear need for continued satellite mass spectrometer and accelerometer measurements over different levels of solar activity if more comprehensive empirical models of thermosphere tides are to be developed.

In a similar vein, J. M. Forbes and H. B. Garrett investigate the electrodynamic effects of the model tidal winds in a paper entitled Solar Tidal Wind Structures and the E-Region Dynamo.[4] Here electric fields, currents, and magnetic variations due to "dynamo action" in the E region are computed and compared with experimental data. The dynamo computations are generally in good agreement in amplitude and phase with the diurnal and semidiurnal harmonics of the observed ground variations at minimum and maximum levels of solar activity. There are, however, real discrepancies on the order of 20% in amplitude and 1 to 2 hr. in phase which require explanation. In addition, nighttime electric fields appear to require coupling mechanisms with the F-region and magnetosphere in order to obtain consistency with observations. In interpreting our theoretical simulations, we attempted to point out the structural features of the E-region tidal winds and conductivities which are most critical to establishing a consistency between theory and experiment, and to evaluate the status of dynamo theory with particular regard to the structure and variability of the solar tidal winds.

The three-dimensional numerical computation of tidal structures in the thermosphere is expensive computationally. This led to development of a formalism for approximating tidal structures in a spherical, rotating, viscous atmosphere by 'equivalent gravity waves' (EGW's) on an f plane: the frequency and zonal wavenumber of the EGW is chosen to match that of the simulated tidal mode; then, for a given planar rotation rate f the meridional wavenumber of the EGW is determined by matching the vertical structure (equivalent depth) of the tidal mode in the absence of dissipation. Simulations are performed for the thermospheric extensions of the first two symmetric and antisymmetric semidiurnal tidal modes and compared to a full numerical treatment of the inseparable tidal equations in the thermosphere to demonstrate the adequacy of this approximation under certain conditions. Development of this technique forms the basis for investigation of a number of problems associated with thermospheric tides which might otherwise be precluded by computer limitations, such as (a) extensive diagnostic studies of seasonal or solar cycle variations in vertical tidal structures at a single location (i.e., an incoherent scatter facility such as Millstone Hill); (b) simulation of the mutual interaction between the dissipation of short-wavelength modes in the mesosphere and the turbulence which they generate; (c) investigation of migrating-nonmigrating tidal coupling, as generated by longitudinal variations in background atmospheric and ionospheric structures, or thermal excitation; (d) construction of a multi-component thermospheric model which includes diffusive interaction between constituents and which can be utilized to test the validity of numerical models which have relaxed this assumption; or (e) extending meteor radar observations of tides into the E and F regions. The usefulness of the EGW formalism in the above applications is particularly relevant for short-wavelength modes which require high resolution in both latitude and height in a full spherical calculation. This work is described in Tides in the Joint Presence of Friction and Rotation: an f-Plane Approximation[5] by J. M. Forbes and M. E. Hagan.

Subsequently, a binary gas ($O-N_2$) extension of the f-plane EGW formalism was developed to study the effects of mutual diffusion between O and N_2 on tidal dynamics, and in particular to examine the damping of oscillations due to partial relaxation of atomic oxygen to diffusive equilibrium for diurnal and semidiurnal tides in the thermosphere. Compared to calculations which omit $O-N_2$ mutual diffusion, diffusive damping acts to reduce the temperatures and horizontal velocities associated with the diurnal thermospheric tide excited in situ by less than 15% with negligible shifts in phase, and to reduce by roughtly 20-40% amplitudes of the semidiurnal tide excited in situ, and the (2,2) and (2,4) modes propagating from the mesosphere, accompanied by 1 to 4 hour shifts in phase. These results affect the interpretation of incoherent scatter measurements of thermospheric tides and the construction of s ynthesized tidal models which are calibrated by these measurements, and suggest that the inequality of the vertical transport velocities of O and N_2 be accounted for in three-dimensional numerical models of semidiurnal thermospheric tides. This work is described in the manuscript Tidal Dynamics and Composition Variations in the Thermosphere[6] by J. M. Forbes and M. E. Hagan.

As a follow-on to the Forbes[3] study, and as part of an effort to interpret accelerometer data from AF satellite experiments under AFGL contract F19628-76-C-0089, the seasonal-latitudinal tidal structures of O, N_2, and total mass density in the thermosphere have been investigated using the theoretical model of Forbes[3] and observational data from Atmosphere Explorer satellites. Atomic oxygen variations are found to be strongly influenced by seasonal differences in the tidal winds, whereas N_2 responds primarily to temperature which has a different seasonal dependence than the winds. The tidal variation of total mass density is complicated by its dependence on the relative amplitudes and phases of the O and N_2 variations. The net effect is that rather complicated and different seasonal-latitudinal variations in tidal structures of O, N_2, and total mass density are predicted to occur. The limited satellite data that are available for the determination of tides support the theoretical results. The existence of such seasonal-latitudinal effects explains why the MSIS model, which is based heavily on midlatitude (AE-C) data below 200 km, predicts an incorrect diurnal phase structure of thermospheric density at equatorial latitudes (as determined from AE-E measurements). This work is described in the manuscript Seasonal-Latitudinal Tidal Structures of O, N_2, and Total Mass Density in the Thermosphere by J. M. Forbes and F. A. Marcos.

In an effort to tie together much of the recent theoretical work on atmospheric tides, the review paper Theoretical Studies of Atmospheric Tides[8] by J. M. Forbes and H. B. Garrett was written. In this review advances in the theory of atmospheric tides since the monograph by Chapman and Lindzen (1970) are comprehensively reviewed. Major developments include investigations of the effects of mean zonal winds and meridional temperature gradients, molecular viscosity and thermal conductivity, radiative damping, composition variations, and hydromagnetic coupling, including seasonal and solar cycle effects. Linearized inviscid and viscid equations of general applicability are documented in this review, and a number of quantitative studies of atmospheric tides are considered as simplifications or modifications of these equations. Recent calculations of thermal excitation due to insolation absorption by H_2O and O_3 below 80 km, UV and EUV absorption in the lower thermosphere, and latent heat release in the tropical troposphere are presented. Although no attempt is made to exhaustively review incoherent scatter, meteor radar, and satellite mass spectrometer contributions to the study of atmospheric tides, representative wind, temperature, and composition data from these sources are interpreted within the framework of the most recent quantitative models, and the current status of our understanding of atmospheric tides is assessed. Some potentially fruitful areas of future research are also presented.

Under a special NSF-funded cooperative sciences program between the U.S. and Japan, this investigator was afforded the opportunity to participate in a seminar on atmospheric tides in Fukuoka, Japan, November 14-16, 1979. Most of the work presented at this seminar was supported by AFOSR-77-3223. A summary of the presentation is found in Mesospheric and Thermospheric Tides[9] by J. M. Forbes.

As part of a continuing effort to study the manifestation of tidal effects in minor constituent variations in the upper atmosphere, a time-dependent chemistry code was developed to investigate the effects of atmospheric tides on D and E region ion chemistries. In Tidal Effects on D and E Region Ion Chemistries[10] by J. M. Forbes, numerical simulations are presented which demonstrate that diurnal and semidiurnal oscillations in temperature and O, O_2, and N_2 densities can produce asymmetries of D and E region electron concentrations about noon similar to those observed experimentally. In the D region it is assumed that NO^+ is the precursor ion in a chain which involves three-body formation of the intermediary cluster ions $NO^+(H_2O)_{m-1}$ (x) (m=1-3) where X can be N_2, O_2, H_2O, or CO_2, switching reactions which convert these weakly bound clusters to hydrates of NO^+ with H_2O to initiate the chain to form $H^+(H_2O)_n$ (n=1-7). The rates of three-body and thermal breakup reactions are affected by tidal oscillations in the ambient temperature and total density. For instance, lower (higher) temperatures enhance (inhibit) the formation of clusters and inhibit (enhance) their thermal breakup, thus reducing (increasing) the electron concentration since the recombination coefficients of cluster ions increase with cluster size and are all large compared with that of NO^+. In the E-region ion production is affected by variations in the attenuation of solar flux due to optical depth changes of the overlying atmosphere, as well as local changes in O, O_2, and N_2 densities. A noon bite-out in D-region electron concentrations, which is sometimes observed experimentally, could not be simulated with the present model. Further, a noon bite-out at midlatitudes cannot be produced via modulation of the electron concentrations by any reasonable tidal variation in electron-neutral collision frequency (it is the product of these quantities which is actually inferred from the measurements). It is suggested that such an effect might be produced by temperature oscillations associated with a gravity wave propagating through the region, or a time variation in NO concentrations due to vertical transport by tides, gravity waves, or changing eddy mixing rates.

There are two studies which have been initiated under AFOSR Grant 77-3223, but will have to be completed under AFOSR Grant 81-0090. The first of these involves utilization of the Forbes and Hagan[5] EGW f-plane model to investigate the cascade of energy from stable tidal waves to waves of smaller scale which eventually go unstable. This theory assumes that tides contribute to the turbulence of the 80 to 100 km region via a cascade mechanism of the type

$$T_{\lambda} \sim T_{\lambda^*} \left(\frac{\lambda}{\lambda^*}\right)^{\alpha}$$

$$W_{\lambda^*} \sim \frac{\omega T_{\lambda}}{\Gamma} \left(\frac{\lambda}{\lambda^*}\right)^{\beta}$$

where T = temperature

W = vertical velocity

ω = frequency

$\Gamma = \dfrac{dT_o}{dz} + \dfrac{g}{c_p}$ = static stability

λ = wavenumber

α, β = "power laws" of cascade processes (each probably $\simeq \frac{1}{3}$)

It can be shown that this results in an eddy diffusion coefficient given by

$$D = D_{max} \left(\frac{\lambda T}{\Gamma}\right)^{\frac{2-\alpha+\beta}{1-\alpha}}$$

where $\lambda T = \dfrac{\partial \delta T_{diurnal}}{\partial z}$, and if $\dfrac{\lambda T}{\Gamma} > 1$ then $\dfrac{\lambda T}{\Gamma}$ *is set equal to 1.* D_{max} *is the* eddy diffusion coefficient which causes exponential growth of the tidal oscillation to cease. To compute D, we first determine D_{max} by choosing arbitrary values for the tidal fields at the ground, and increase D in successive computer runs (D is taken to be constant with height for a given case) until the tidal fields attain constancy with height. For the (1,1) propagating tidal mode, this gives $D_{max} = 2 \times 10^6$ $cm^2 sec^{-1}$. Then, an f-plane calculation with realistic thermal excitation and "almost inviscid" eddy diffusivity ($D=10^3 cm^2 sec^{-1}$) is performed, and a new D profile constructed from the above equation. This "zeroth iteration" yields temperature amplitudes for the (1,1) mode which increase from 10K to 300K between 70 and 110 Km, and a D profile that increases in amplitude over this height range from $6 \times 10^4 cm^2 sec^1$ to $2 \times 10^6 cm^2 sec^{-1}$ (see Figures 1 and 2). A new tidal calculation is then performed, this time using the updated D profile, thus obtaining a second temperature profile from which a new D can be computed. This process is iterated until a converged solution is achieved such that the final macroscopic tidal fields and the final eddy diffusion profiles are consistent with one another. The final results, illustrated in

Figures 1 and 2, indicate increases between 70 and 110 km of 10K to 75K for temperature and $1.5 \times 10^5 cm^2 sec^{-1}$ to $2 \times 10^6 cm^2 sec^{-1}$ for D. This work is planned for publication in a note tentatively entitled Tidal Breakdown and Turbulence in the Mesosphere and Lower Thermosphere by R. S. Lindzen and J. M. Forbes.

The second uncompleted project involves a comprehensive model of the diurnal tide from the surface to 400 km, and detailed interpretation of the results in the light of available surface barometric, rocket, balloon, radar, and satellite data. Sample computer-generated plots of the tidal fields at solstice as a function of height and latitude are shown in Figures 3-6. This work is currently being written up in articles entitled Atmospheric Tides - I. Governing Equations and Model Parameterizations and Atmospheric Tides - II. The Solar Diurnal Component, by J. M. Forbes. Due to the magnitude of these efforts, Parts I and II are jointly funded by AFGL Contract F19628-76-C-0089. Parts III, IV, and V of this study, dealing respectively with the solar semi-diurnal, lunar semidiurnal, and solar terdiurnal tides, are being funded by AFGL and NSF (not AFOSR).

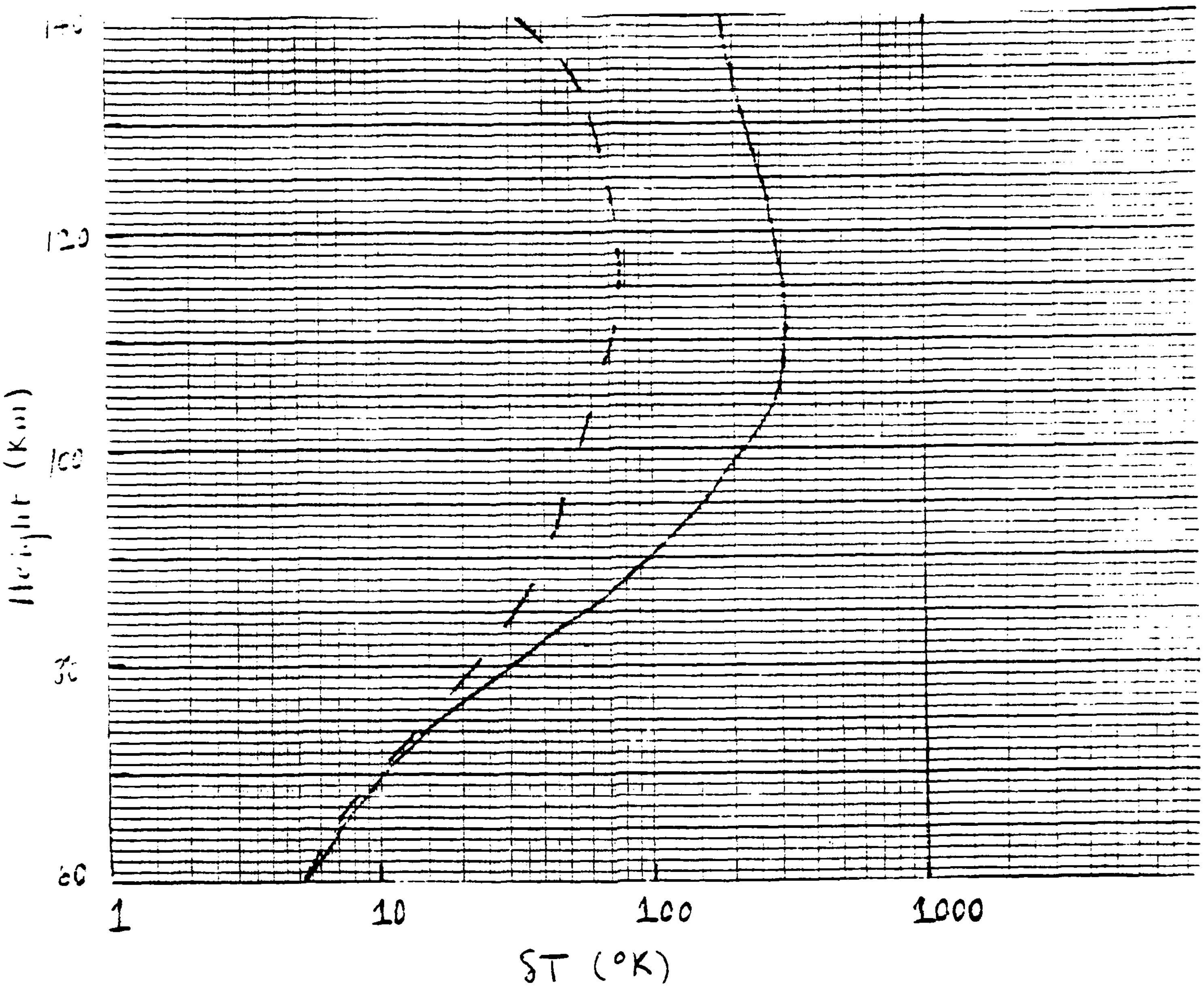

Figure 1. "Zeroth iteration" (——) and "converged" (---) temperature profiles assuming $\alpha = \beta = \frac{1}{3}$ power laws for energy cascade associated with (1,1) propagating diurnal tide.

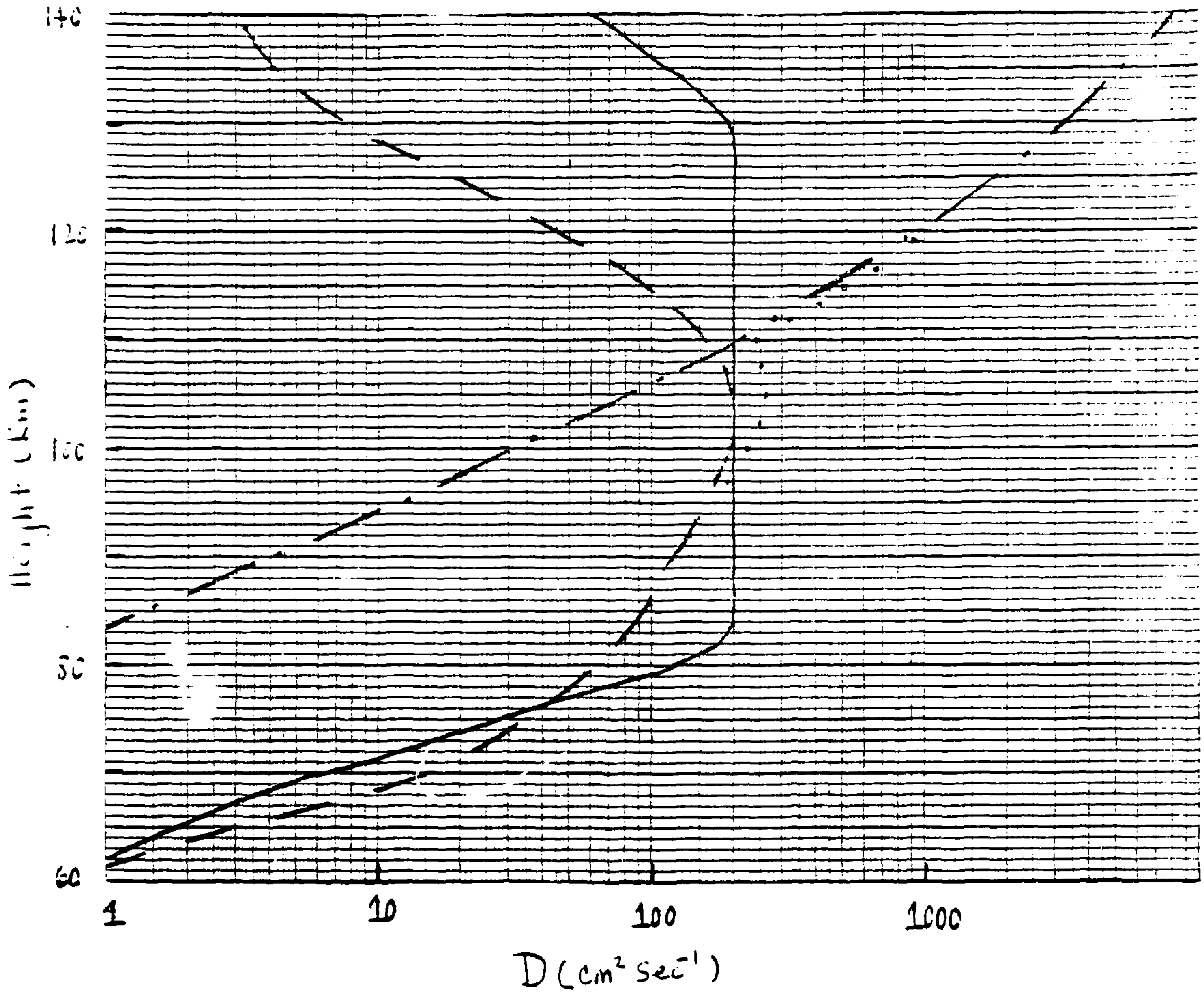

Figure 2. "Zeroth iteration" (——) and "converged (---) eddy diffusion profiles corresponding to the temperatures in Figure 1. Also shown are molecular diffusion coefficient (- • -), and sum of eddy and molecular diffusion coefficients (•••).

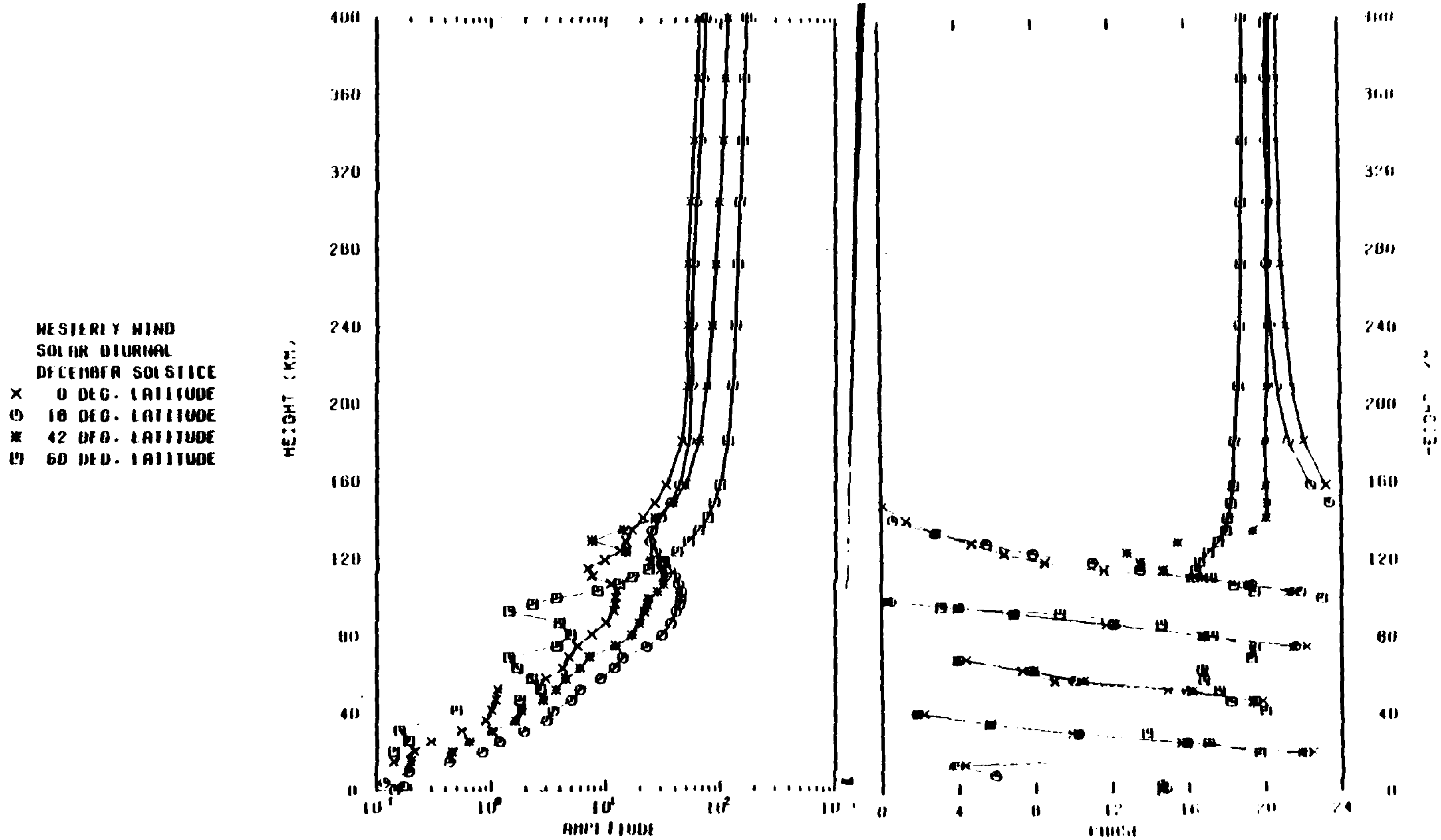
WESTERLY WIND
SOLAR DIURNAL
DECEMBER SOLSTICE
× 0 DEG. LATITUDE
⊖ 18 DEG. LATITUDE
* 42 DEG. LATITUDE
⊟ 60 DEG. LATITUDE
HEIGHT (KM)
AMPLITUDE
PHASE
0
40
80
120
160
200
240
280
320
360
400
4
8
12
16
20
24

Figure 3

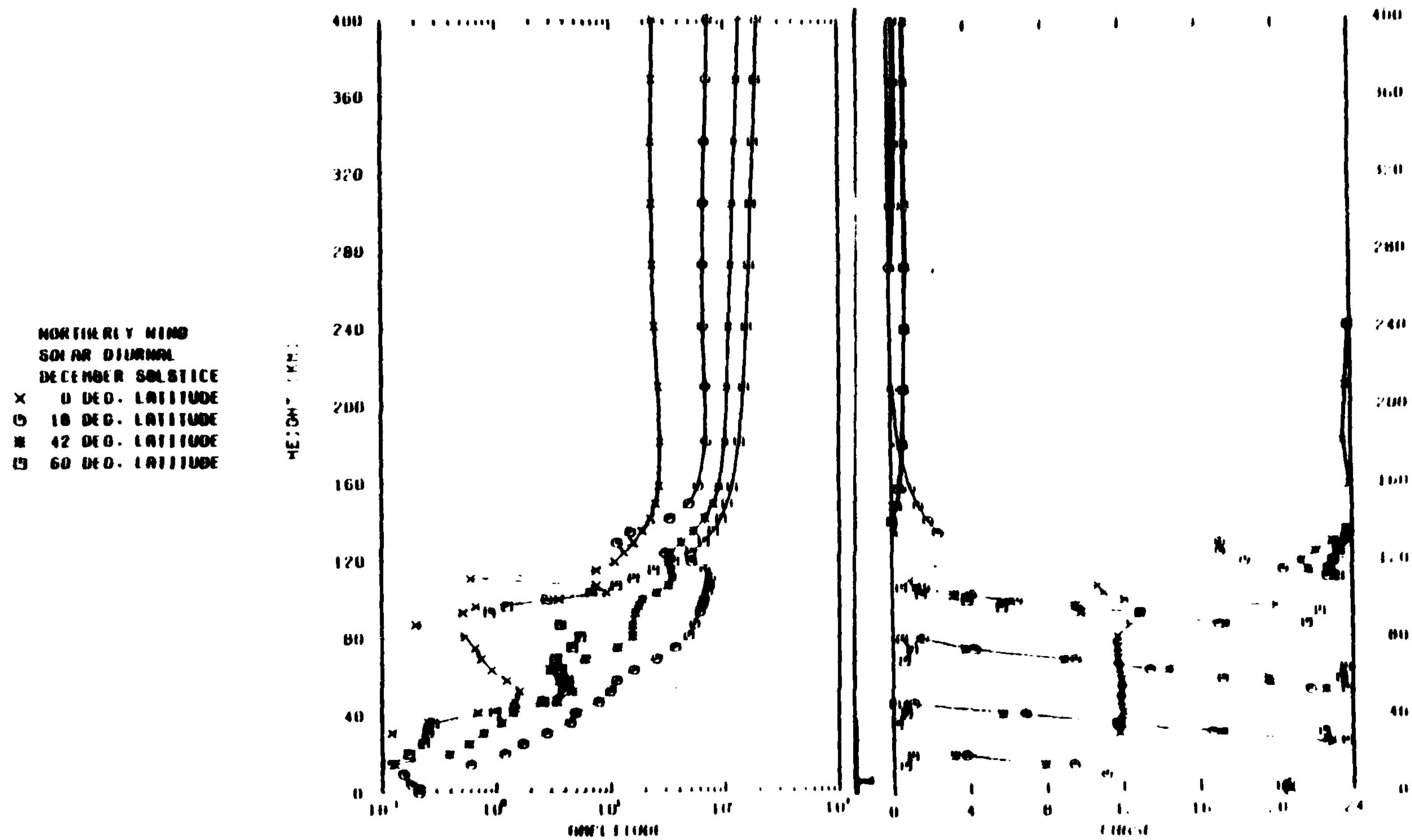
NORTHERLY WIND
SOLAR DIURNAL
DECEMBER SOLSTICE
× 0 DEG. LATITUDE
⊙ 18 DEG. LATITUDE
✱ 42 DEG. LATITUDE
⊡ 60 DEG. LATITUDE
HEIGHT (KM)
AMPLITUDE
PHASE
400
360
320
280
240
200
160
120
80
40
0
4
8
16
24

Figure 4

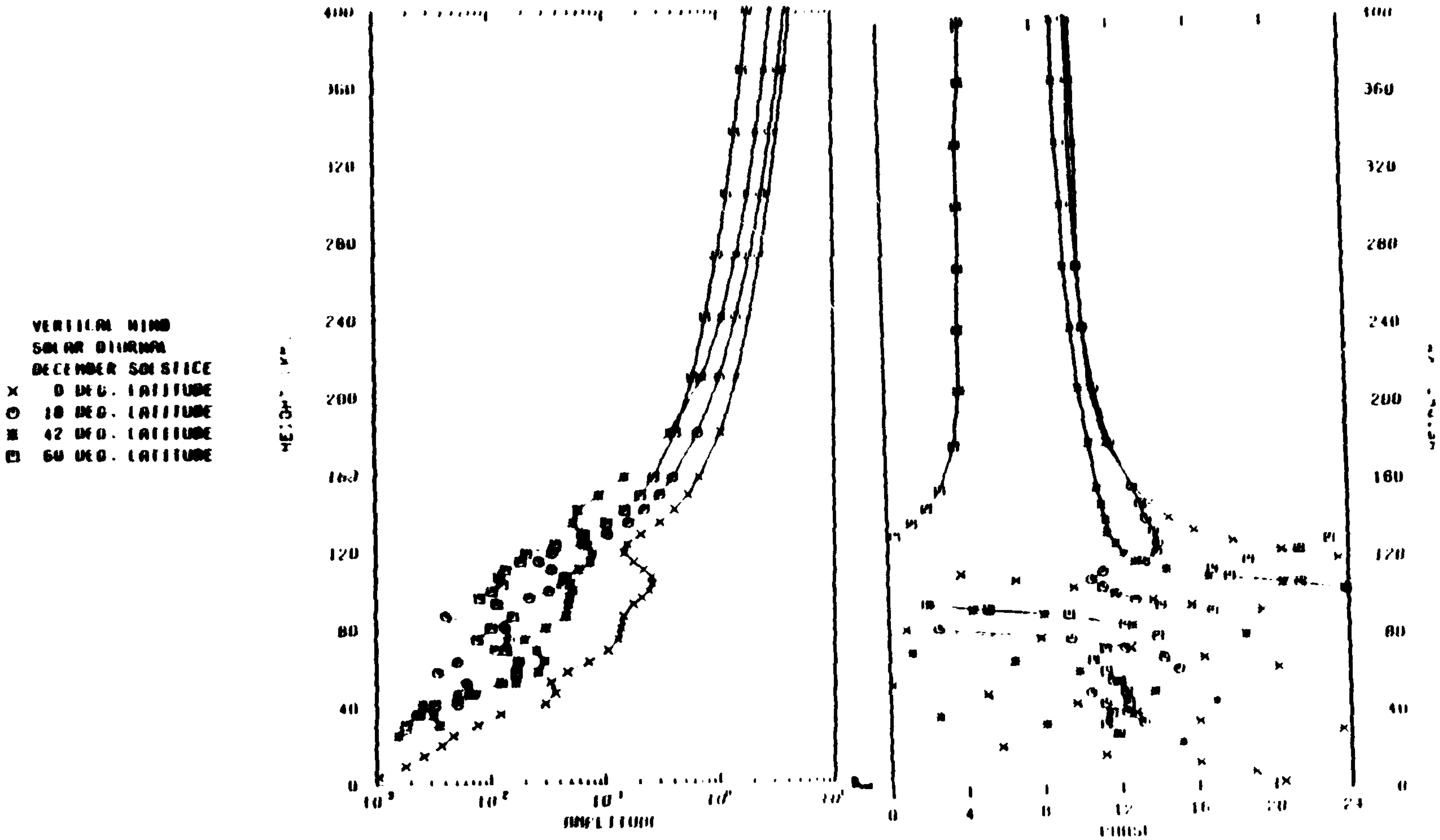
VERTICAL WIND
SOLAR DIURNAL
DECEMBER SOLSTICE
× 0 DEG. LATITUDE
⊖ 18 DEG. LATITUDE
✱ 42 DEG. LATITUDE
⊡ 60 DEG. LATITUDE
HEIGHT (KM)
AMPLITUDE
PHASE
0
40
80
120
160
200
240
280
320
360
400
0
4
8
12
16
20
24

Figure 5

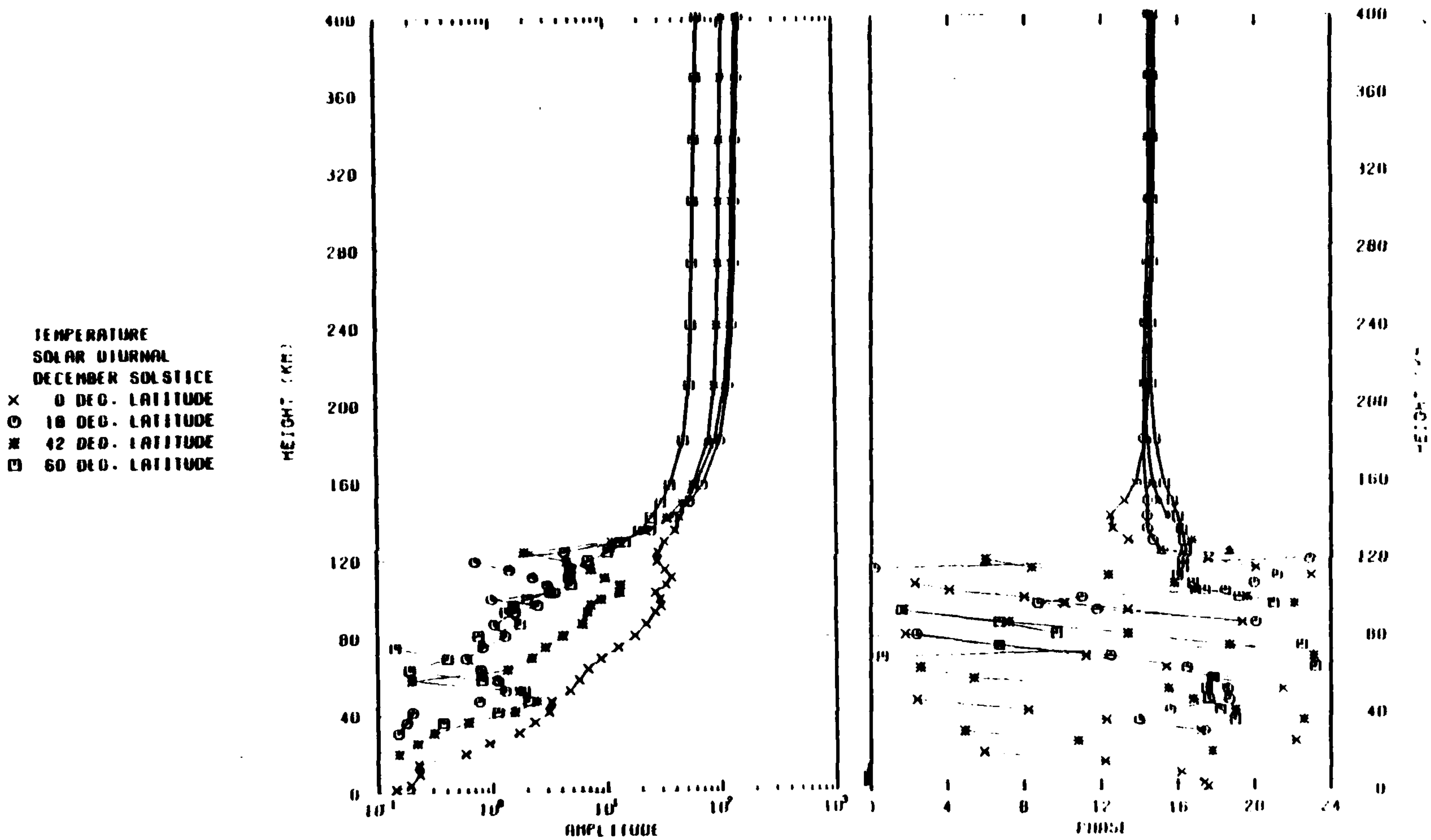
TEMPERATURE
SOLAR DIURNAL
DECEMBER SOLSTICE
× 0 DEG. LATITUDE
⊖ 18 DEG. LATITUDE
✱ 42 DEG. LATITUDE
◫ 60 DEG. LATITUDE
HEIGHT (KM)
AMPLITUDE
PHASE

Figure 6

CUMULATIVE LIST OF PAPERS COMPLETED
UNDER GRANT AFOSR-77-3223

1. Forbes, J. M., and H. B. Garrett, Seasonal-Latitudinal Structure of the Diurnal Thermospheric Tide, J. Atmos. Sci., 35, 148-159, 1978.

2. Garrett, H. B., and J. M. Forbes, Tidal Structure of the Thermosphere at Equinox, J. Atmos. Terr. Phys., 40, 657-668, 1978.

3. Forbes, J. M., Tidal Variations in Thermospheric O, O_2, N_2, Ar, He, and H, J. Geophys. Res., 83, 3691-3698, 1978.

4. Forbes, J. M., and H. B. Garrett, Solar Tidal Wind Structures and the E-Region Dynamo, J. Geomag. Geoelec., 31, 173-182, 1979.

5. Forbes, J. M., and M. E. Hagan, Tides in the Joint Presence of Friction and Rotation: An f-plane Approximation, J. Geophys. Res., 84, 803-810, 1979.

6. Forbes, J. M. and M. E. Hagan, Tidal Dynamics and Composition Variations in the Thermosphere, J. Geophys. Res., 85, 3401-3406, 1980.

7. Forbes, J. M., and F. A. Marcos, Seasonal-Latitudinal Tidal Structures of O, N_2, and Total Mass Density in the Thermosphere, J. Geophys. Res., 85, 3489-3493, 1980.

8. Forbes, J. M., and H. B. Garrett, Theoretical Studies of Atmospheric Tides, Rev. Geophys. Space Phys., 17, 1951-1981, 1979.

9. Forbes, J. M., Mesospheric and Thermospheric Tides, J. Meteorol. Soc. Japan, 58, 298-301, 1980.

10. Forbes, J. M., Tidal Effects on D and E Region Ion Chemistries, in press, J. Geophys. Res., 1981.

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